First Electro-Optical Detection of Charged Particles

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Abstract

We have made the first observation of a charged particle beam by means of its electro-optical effect on the polarization of laser light in a birefringent crystal. The modulation of the laser light during the passage of a pulsed electron beam was observed using a fast photodiode and a digital oscilloscope. The fastest rise time measured in a single shot, 120 ps, was limited by the bandwidth of the oscilloscope and the associated electronics. This technology holds promise for detectors of greatly improved spatial and temporal resolution for single relativistic charged particles as well as particle beams.

An effort has been initiated to develop an ultra-fast charged particle detector based on the birefringence, and hence the phase difference induced between orthogonal components of polarization (ellipticity), in an optical medium by the electric field of a relativistic charged particle [1]. The electro-optical effect in amorphous optical media is known as the Kerr effect [2] and is quadratic in the electric field E. In uniaxial crystals the induced ellipticity is linear in the E-field and is known as the Pockels effect [3]. The induced phase delay can then be given by $\phi = \pi(V/V_\pi)$ with V the applied voltage and V_π the voltage required for producing a phase shift between orthogonal components of polarization equal to π radians or an ellipticity of $\pi/\sqrt{2}$ since the maximum ellipticity is induced when the polarization is at 45° with respect to the applied electric field direction.

The passage of a tightly bunched relativistic electron beam within several millimeters of a commercially available LiNbO3 crystal [4] coupled to polarization maintaining fibers of 4 microns diameter propagating polarized infrared light ($\lambda = 1.32\mu$m) was observed by the effect of a microbunched electron beam on the polarization of the light in the crystal. This was determined by means of a $\lambda/4$ plate which converted the induced ellipticity to a rotation of the initial linear polarization which had previously been nearly extinguished by the analyzer (crossed polarizer). The resulting modulation of the transmitted laser light was detected by a photodiode of 45 GHz bandwidth and pre-amplifier. The output signals were digitized in a 7 GHz sampling oscilloscope and stored in memory. The optics setup is indicated in Fig.1

A bunched charged particle beam creates an electric field, E, at a distance r that is well approximated by Coulomb's Law multiplied by γ, the relativistic Lorentz factor, and N_e the number of particles in the beam bunch for a minimum distance $r_0 \gg$ than the dimensions of the beam bunch. The $LiNbO_3$ crystal had $V_\pi = 5$ V with an electrode separation of 15μm and a length of $l = 1.5$ cm. The integral $\int E\,dl = \int 5V/(15\times10^{-6}\,\mathrm{m})\,dl = 5000$ V produces $\pi/\sqrt{2}$ radians maximum ellipticity.

The integral of the electric field of the particle bunch over the crystal dimensions for a beam bunch located at the mid-plane orthogonal to the length of the crystal at a distance r_0 is

$$\int Edl = \frac{N_e\gamma q}{2\pi\epsilon_0 r_0}(1-\sin\theta) \qquad (1)$$

where θ is the angle subtended by the crystal length, l and the direction to the beam center from the end of the crystal. For $r_0 = 5$ mm, $\int Edl =$

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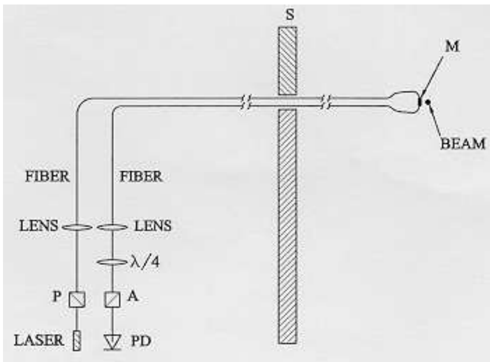

Figure 1. The experimental setup for detecting a charged particle beam. The $LiNbO_3$ crystal was located at the beam position indicated by E-field. The positions of the polarizer (P), lenses (L), analyzer (A) and photodiode detector(D) are schematically indicated.

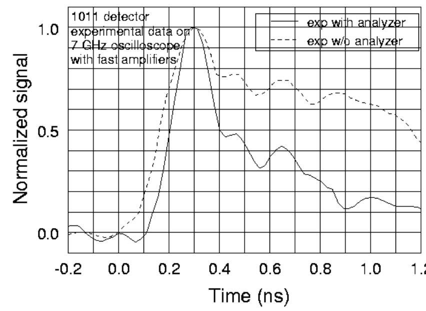

Figure 2. The polarization dependent signal (solid line). The electron beam was ≈ 0.5 cm from the crystal. The polarization independent signal is indicated by the dashed line.

$2.6 \times 10^{-7} \gamma N_e$V which should yield an ellipticity of $\phi = \gamma N_e \times 0.1$ nradian. The signal to noise ratio for a measurement of this type that is photon statistics limited is given by

$$SNR = \phi \sqrt{\frac{PTq_p}{2h\nu}} \qquad (2)$$

where P is the laser power, T the time resolution or inverse of the detection system bandwidth, q_p the quantum efficiency of the photodiode, and $h\nu$ the laser photon energy.

A 45 MeV kinetic energy electron beam at the Brookhaven National Laboratory Accelerator Test Facility containing up to 1 nC in a diameter of approximately 1 mm with 10 ps duration and a repetition rate of 1.5 Hz was scanned across the crystal. Measurements were made in the single shot mode. The extinction was generally close to 10^{-3}.

With $\gamma = 88$, $P = 10$ mW, $T = 100$ ps and $q_p = 0.8$ and $h\nu = 0.9$ eV, Eq.2 gives the required number of electrons in the beam for $SNR = 1$, $N_e \sim 6.8 \times 10^4$ for detection of a single beam bunch. However, the 7 GHz bandwidth limits the sensitivity to the inherently much faster signal by as much as factor of five implying $\approx 3 \times 10^5$ singly charged particles are required for detection of a single ATF beam bunch. The ATF beam of $N_e = 6.3 \times 10^9$ per bunch was sufficient to generate a detectable signal. The maximum modulation of the light intensity was about 9% of its DC level.

The polarization dependent signal is displayed in Fig. 2 (solid curve). A signal was also obtained when the crystal intercepted the beam (dashed curve) which was found to be independent of the analyzer and hence is polarization independent. It does not change sign with polarization orientation and it has a significantly longer decay time constant than the polarization dependent signal.

In order to achieve single particle detection with enhanced time resolution, a high power pulsed laser of 10^8 W, e.i. 10mJ for 10 ps and a transient digitizer of greater bandwidth, e.g. 100 GHz would require $\gamma N_e \approx 20$ for single charged particle detection with a $SNR = 1$. The use of a high power pulsed laser would preclude the detection of randomly occurring events because of the inability to trigger the laser. However, this would not be a problem at colliding beams machines where the beams are bunched to maximize the luminosity. Particles of $\gamma Z > 20$ would be detectable at RHIC and the LHC.

A detector constructed of parallel rows of electro-optical crystals with a separation of 100μ m would easily provide single particle detection in LiNiO3 based detectors. However, the small size and high cost of these crystals would severely limit their applicability.

We have recently produced poled optical fibers [5]. If they or other moderately priced electro-optical materials can yield adequate sensitivity for single particle detection, a new generation of ultrafast fine grained charged particle detectors may be at hand.

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